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## Cross-measure directional drilling

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# CROSS-MEASURE DIRECTIONAL DRILLING

Frank Hungerford<sup>1,2</sup> and Ting Ren<sup>1</sup>

**ABSTRACT:** The development of directional drilling in the coal industry has been driven by the need to provide reliable in-seam gas drainage ahead of development. The same technology has been utilised for cross-measure drilling in adjacent seams other than the working seam and also in surrounding strata. The equipment and technology utilised for the applications of directional drilling in cross-measure applications is identified. The process of designing both lateral and vertical aspects of the drilling is explained with specific reference to the limitations and practices of directional control during the inter-burden section of each borehole. Cross-measure drilling applications of in-seam pre and post gas drainage, goaf gas drainage, water management and in-rush protection as well as exploration are described to explain the ways the technology has been utilised.

## INTRODUCTION

Although underground drilling has evolved from rotary drilling to directional drilling for gas drainage, the ability to steer and locate boreholes with directional drilling has created opportunities to access horizons (or targets) other than that of the drill site location.

As with in-seam drilling, it is essential to have prior knowledge of the environment to be drilled. This allows logical limitations to be applied to project planning to ensure equipment security and enhance the prospects of achieving favourable goals. The in-seam component is similar to directional in-seam drilling. The added challenge involves dealing with the variations presented with the cross-measure component. Borehole design has to provide a design path in the vertical plane usually complicated by being incorporated with a lateral design path. The drillers then attempt to follow these paths while dealing with the variability of environment with changing strata and stability.

The various applications of cross-measure and cross-measure in-seam drilling have been developed and employed in Australia, the USA, China and other countries. These have their challenges in both the planning and the drilling stages.

## DIRECTIONAL DRILLING

While in-seam rotary drilling was being used for gas drainage, rotary drilling was and still is employed to drill relatively straight boreholes angled through the strata and coal measures under and over longwall blocks. These boreholes provide post-drainage by removing gas released from the underlying seams after stress relief as the longwall face passes. In some instances, similar boreholes have been drilled into the strata above the longwall block to provide gas drainage of the goaf.

Directional drilling has provided the ability to drill boreholes through, into and along strata surrounding the working seam. Early application of cross-measure, in-seam direction drilling was trialled as part of an in-seam directional development project (Hungerford, *et al.*, 1988) and has since evolved as an established practice. This provides the opportunity to locate boreholes in positions which can provide pre and post gas drainage, exploration, water drainage and inrush protection.

The equipment used is the same as for in-seam directional drilling with some allowances for the various vertical angles at the collar and options to manage unstable environments and stronger strata in the cross-measure sections. Although the required capacity of a drilling system for cross-measure is dependent of the length of boreholes to be drilled, the established standard equipment set for longhole drilling in the 1980's and 90's (Hungerford, 1995) includes:

- 75 kW, 1000 v electro-hydraulic power unit,

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- Integrated methane monitor,
- 250 l/min at 8 MPa high pressure water pump,
- 135 kN thrust and pull,
- 1500 to 2000 Nm torque, NQ rod capacity rotation unit,
- track mounted,
- compact enough to operate in a mine roadway and allow vehicles to pass.

The specifications for directional drilling equipment have been upgraded with an HQ rod chuck capacity for over-core recovery. Since there will always be some uncertainty in the stability of the environment to be drilled and no fall-back recovery option of mining recovery of bogged equipment, the option of over-coring needs to be available with the HQ rod capacity. To supplement that precaution, if boggy conditions are expected, the design depths need to be limited to the over-coring depth capacity. If cross-measure drilling is the main aim of a drilling project, it is preferred that the feed frame of the drill rig be supplied with an angled setup option so standpipes can be installed at appropriate vertical angles to suit the design of the project. Track mounted drill rigs are limited in the vertical angle at which they can be mounted.

CHD rods are utilised with an electronic survey tool and 2-7/8" downhole motor. Electronic survey tools are an integral component in the process of steering the drilling.

The standard 4/5 lobe Accu-drill downhole motor has been used extensively in cross-measure drilling with good results. Penetration rates are dependent of the strength of the strata being drilled with 0.2 m/min a common penetration rate in the sandstone with a compressive strength in the order of 60 MPa. Recently, more powerful 5/6 and 7/8 lobe downhole motors have been introduced with good drilling performance.

The PCD bit design impacts on penetration rate and performance. Drill bits from Asahi and Drilling Products Inc. (DPI) have been used with various options available in the shape of the face (convex versus flat) and arrangement of cutters. Some bits of a particular design have been very effective then following supplies have suffered from quality control problems which tend to negate previous reputations gained. In each case, the drillers have to assess how the current bit is performing, alter drilling parameters to establish reasonable penetration rates or ultimately replace the bit. Reliability and robustness then become as important to the performance of the drill bit. Inter-burden strata strength has a direct influence on the penetration rates achievable and when it exceeds 60 MPa, penetration rates can be expected to reduce dramatically. In these cases, the option of using tungsten tipped tri-cone roller bits for the stone section of drilling is available but only over short intervals due to the limited life of these bits in this environment.

## DRILLING ENVIRONMENT

As for any directional drilling, an assessment of the expected drilling conditions is required. Not only does it serve to provide the drillers with an indication of what to expect and what precautions they may need to employ, but it also has an influence on the design of the drilling. Ideally, the drilling environment needs to be stable enough to support an open borehole over the length of the drilling along the target horizon, and for long enough through the cross-measure section to allow for installation of casing if required. The state of the strata at the drill site determines whether the standpipe is installed directly into the face or has to be directed into the roof or floor strata.

Since access is not usually available to inspect the inter-burden strata and seams, initially the drilling relies on studying geological logs from any existing vertical exploration boreholes in the area. Some idea of the nature and stability of the inter-burden strata can be defined but ultimately, the most comprehensive knowledge is established from prior and current experience in drilling the environment. The presence of fractured horizons and clay bands with the expectation of swelling when in contact with water is the main point of caution. Prior knowledge of thick soft clay bands has shaped drilling projects by limiting drilling to targeting coal seams above the clay band to avoid intersection/interaction. If substantial clay bands are to be penetrated, a reliable plan needs to be established involving drilling a pilot borehole, reaming and installing casing through the area to allow unimpeded drilling beyond.

With any drilling, the drilling horizon has to be reasonably stable to allow drilling to progress. The drilling horizon has to support the initial drilling and then the borehole has to remain open to be effective for its design purpose. Assessment of this also relies on both exploration data and prior experience. The gaining of additional knowledge and experience is an ongoing learning process as drilling progresses. Particular zones of interest are the inter-faces between the stone strata and the target coal seam which have been found to be unstable in many instances and require stabilising by extended flushing and rotation before drilling can continue. It is not uncommon to have to over-core through this section to release a bogged set of rods.

### STRATIGRAPHY OF VERTICAL SECTION

The key information required from the vertical stratigraphy through the coal measures is the thickness and location of the target seam or strata, adjacent coal seams and distinguishing strata in the inter-burden to be crossed. The inter-burden seams and main strata members are used to monitor the progress through the inter-burden and compare relative positions with the vertical design.

The thickness of the target seam and the vertical displacement required to reach it determines the vertical entry angle, angle through the inter-burden and angle at which to intersect the target seam and be able to curve vertically to "land" within the seam to continue the in-seam drilling.

Contours of the working seam (or Reduced Levels (RL's) of the surrounding workings) are required to determine the profile of the target seam both in the area of intersection and along the length of the in-seam section of drilling. For drilling along a horizon in the strata outside the seam, the seam profile provides a reference horizon to which the vertical profile can be designed.

The logical design sequence is to complete the lateral design first then plot it on the mine plan to allow the seam profile along the path of drilling to be determined. The profile of the target seam can be incorporated on that profile and then design the vertical borehole profile to suit.

### LATERAL DESIGN

The lateral design is the relative position left or right of a horizontal reference line along a target azimuth. This allows boreholes to be positioned in specific locations parallel to roadways, at specific spacing or to intersect a known location or feature.

Designing lateral borehole layouts for cross-measure, in-seam or parallel strata drilling is the similar to designing for in-seam drilling (Figure 1). The only variation is specific allowance for the reduced ability to curve laterally when it coincides with a section or borehole which requires a curve in the vertical design. The usual options are to design both vertical and lateral curves at reduced rates so their combined curve is within the capabilities of the downhole motor, design the borehole so the vertical and lateral curves do not coincide (Table 1) or reduce the vertical angle and lateral off-set angle so the extent of curving is reduced.

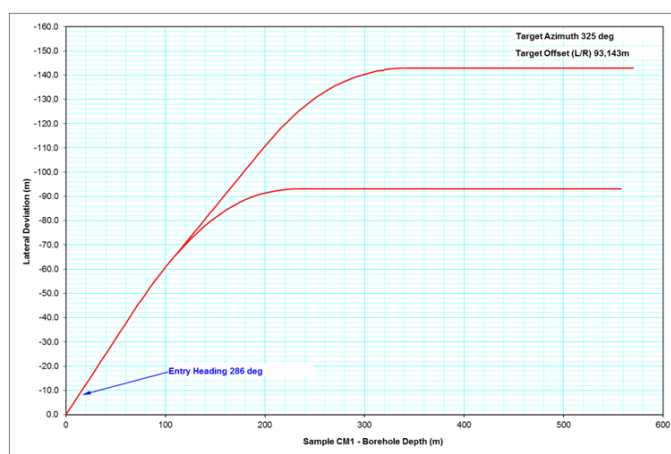


Figure 1 - Lateral deviation design

Table 1 - Design survey data

DEPTH m	AZIMUTH deg	PITCH deg	DRIFT deg	DOWN TRACK	LEFT/ RIGHT	UP/ DOWN
	Entry Hdg					
0	286.00	-7.00	-39.00	0.00	0.00	0.00
6	286.00	-7.00	-39.00	4.63	-3.75	-0.73
12	286.00	-7.00	-39.00	9.26	-7.50	-1.46
18	286.00	-7.00	-39.00	13.88	-11.24	-2.19
24	286.00	-6.00	-39.00	18.52	-14.99	-2.87
30	286.00	-5.00	-39.00	23.16	-18.75	-3.45
36	286.00	-4.00	-39.00	27.81	-22.52	-3.92
42	286.00	-3.00	-39.00	32.46	-26.29	-4.28
48	286.00	-2.00	-39.00	37.12	-30.06	-4.55
54	286.00	-2.00	-39.00	41.78	-33.83	-4.76
60	286.00	-1.00	-39.00	46.44	-37.61	-4.91
66	286.00	0.00	-39.00	51.10	-41.38	-4.97
72	287.50	1.00	-37.50	55.81	-45.10	-4.91
78	289.00	1.50	-36.00	60.62	-48.68	-4.78
84	290.50	1.50	-34.50	65.52	-52.15	-4.63
90	292.00	1.50	-33.00	70.50	-55.48	-4.47
96	293.50	1.50	-31.50	75.58	-58.68	-4.31
102	295.00	1.50	-30.00	80.73	-61.74	-4.15

If multiple legs are required from a single standpipe, the preferred option is to plan any branching after the cross-measure section to improve chances of successful branching and utilise better lateral control in coal compared to stone. In each case, the inner leg of any set is designed first within the limits of lateral deviation rates then additional legs designed as an extension out to a wider lateral deviation.

### VERTICAL PROFILE

When the lateral design is completed, the planned borehole(s) can be plotted on the relevant mine plan to confirm the correct positioning. Using the seam contours along the line of the borehole, the profile of the target seam (and any inter-burden seams) can be incorporated on the profile using the established vertical separation and then design the vertical borehole profile (Figure 2). Adjustments in either vertical or lateral design can be made progressively to bring the design parameters within the capabilities of the drilling.

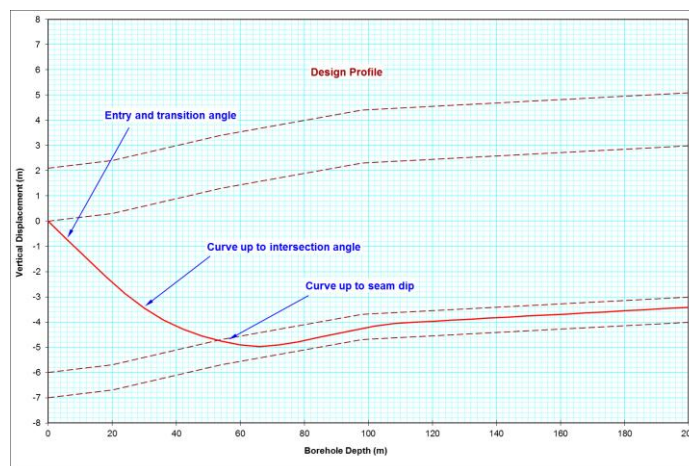


Figure 2 - Design profile of cross-measure in-seam borehole

The vertical entry angle can be determined and limited by several factors including:

- vertical displacement to reach the target seam or horizon,
- any design or distance restrictions within which the target horizon must be reached,
- height of the drill site limiting angled rod handling from the collar, through the drill rig and out the back to the water swivel,
- range of vertical angles at which the drill rig can be mounted,
- height of the feed frame of the drill rig.

Additional allowances are required for rod handling if catering for the ability to over-core in the case of potential bogging in adverse drilling environment. The vertical angle is limited with a single unit, track mounted rig where the hydraulic power unit is incorporated in the rig.

Where the entry angle does not match that required to transect the inter-burden section, the borehole can be curved down or up to achieve the angle required. As drilling progresses through the inter-burden, the strata being penetrating needs to be compared with that of the lithology to monitor progress through the inter-burden. Adjustments can be made to the design vertical profile when the strata is intersected higher or lower than expected. As each inter-burden drilling section is completed, the lithology can be modified to match that defined by the drilling.

The angle transecting the inter-burden may be too big to recover from to remain within the target seam after it has been intersected. The thickness of the target seam or distance into the target seam of the planned drilling dictates the differential angle at which the seam can be intersected while still maintaining the ability to curve vertically to "land" the borehole within the seam. The differential angle is then combined with the dip of the seam in the direction of drilling to determine the vertical angle of drilling desired to intersect the seam. The design has to indicate a point from which to curve the borehole to achieve the desired intersection angle and continue to the seam (Figure 2). From the intersection with the seam, the borehole can then be curved vertically to run parallel with the target horizon in seam or strata. For a very close intersection, a preferred differential angle of three degrees is needed, which only requires three survey intervals to get the borehole parallel to the target horizon.

The stability of the inter-burden and interfaces between strata and seam also has an influence on the vertical angles. The steeper angle of transition through the inter-burden reduces the contact distance through any particular strata and thus reduces the potentially adverse exposure to the strata.

When in-seam drilling, the plan is then to curve the borehole up to intersect the seam roof to confirm the profile before branching to continue the drilling. This practice also provides numerous opportunities for branch points should ongoing drilling encounter unstable conditions. As mentioned earlier, the rate of curve may have to be reduced if coinciding with a section of borehole requiring a lateral curve.

## APPLICATIONS

### Cross-measure in-seam drilling for pre and post drainage

The first example of directional drilling being employed was during the research and development project at Appin Colliery (Hungerford, *et al.*, 1988). Short-hole rotary drilling had been employed to provide post-drainage of gas released from the underlying seams during longwall extraction. An initial vertical cored borehole was drilled from the Bulli seam down through the underlying coal measures. This borehole defined the location and thickness of each coal seam, major stone strata and the presence of clay bands. The presence of a significant (1.2 m thick) soft clay (tuff) band in the upper section of the Wongawilli seam prompted the decision to limit cross-measure drilling to the Balgownie seam (14.09 m below the floor of the Bulli seam) to avoid the potential problems of drilling low angled boreholes through the clay.

The initial trial at cross-measure, in-seam drilling of the Balgownie seam (Hungerford, *et al.*, 1988) from the end of LW15 produced a 923 m long borehole (Figure 3) which was branched for second leg, 857 m long and 40 m to the left. These boreholes produced moderate pre-drainage gas flows before the advancing longwall face crossed the end of the boreholes. From that point, very high gas flows were produced with beneficial gas control at the longwall face. This practice has been tried for other longwall blocks and at other mines (Figure 4) with mixed results in drilling control, gas flows and management.

Directional drilling has allowed drilling to access and provide more contact with the coal seams below each longwall block. With post-drainage applications, the target seam is usually below the current extraction seam with the drilling providing an attempt to pre-drain gas before longwall extraction. With longwall extraction, boreholes are then in position to provide post-drainage by drawing off as much of the released gas as possible. In China, there is a propensity to drive roadways in stone under the seam being mined to provide access for gas drainage rotary drilling. The opportunity exists to drill directional in-seam boreholes from these stone roadways to target the seam above for more efficient pre-drainage of gas.

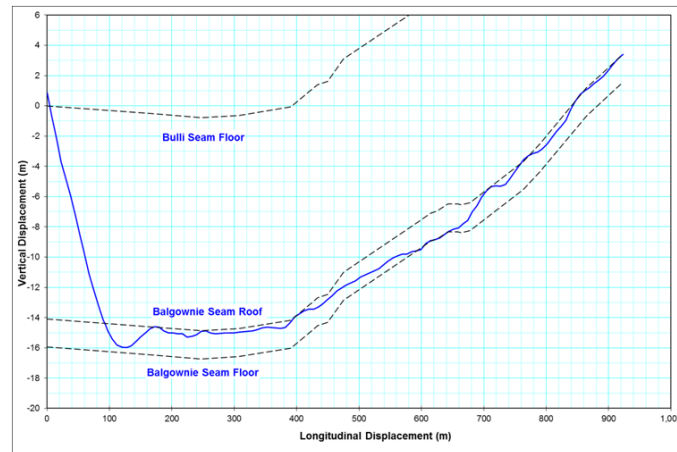


Figure 3 - Initial cross-measure in-seam trial in the Balgownie seam (Hungerford, *et al.*, 1988)

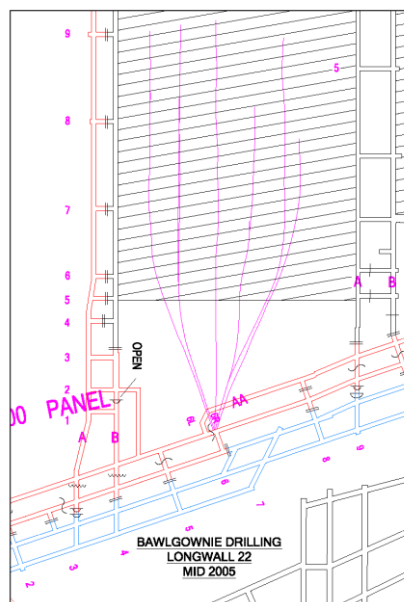


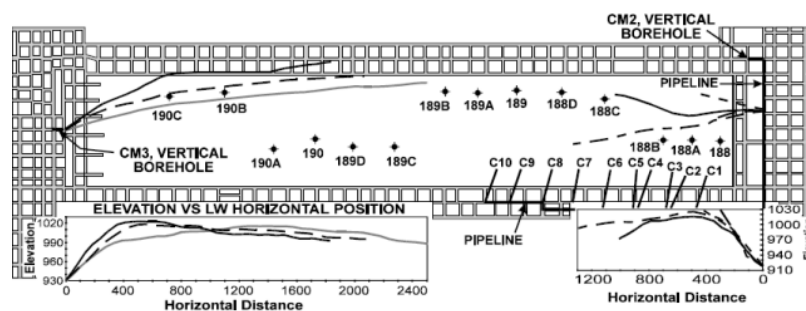
Figure 4 - Successful Balgownie seam cross-measure drilling pattern

Where early exploration in the Appin project identified the soft clay member within the Wongawilli seam as a problem to penetrate and maintain open, drilling in mines to the south found the clay member to be more stable. Drilling through the clay still presents stability problems after exposure to water so the installation of casing is required to allow ongoing drilling. One established practice is to drill the directional borehole through the clay, ream the borehole to a bigger diameter then install casing before continuing with the directional drilling. All drilling, reaming and installation of casing has to be completed within a day before swelling of the clay presents further problems.

A recent development has been to directional drill to the top of the clay, ream out to that depth, drill through the clay with casing fitted with a retractable bit, remove the bit then continue directional drilling. These practices have allowed access to the lower sections of the Wongawilli seam from the Bulli seam for pre-drainage.

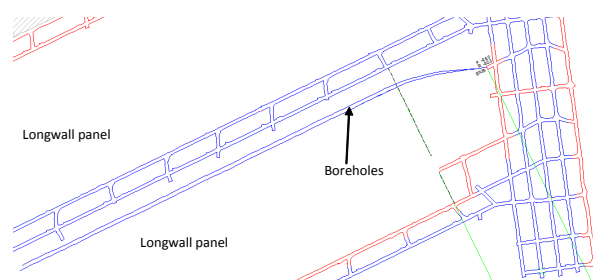
### Goaf drainage

Cross-measure drilling into the strata above and parallel to the working seam has allowed gas to be drained from the goaf to control gas at the longwall face (Figure 5) (Kravits, *et al.*, 1993). This practice has been in place in the USA for some time and has recently been introduced to some Australian mines. In China, there is a practice of driving sewer roadways along the length of the longwall blocks in the stone strata above. To replace these successfully with directional boreholes will provide large cost savings.



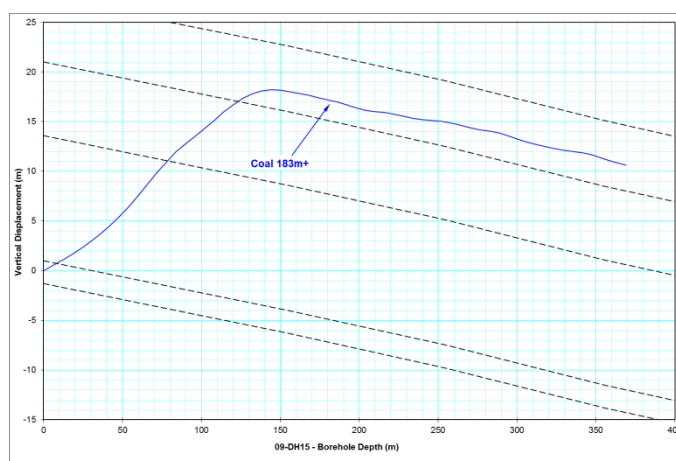
**Figure 5 - Underground directional goaf drainage holes (Kravits, *et al.*, 1993)**

The applications in Australia have been limited but the potential benefits are starting to be realised. Drilling has been directed into the strata above the seam adjacent to the tailgate roadway (Figure 6). These boreholes have been reamed from a diameter of 96 mm to 145 mm to improve gas flow potential. This reaming has limited the borehole lengths to 500 m to be manageable with an alternate set of more robust rods (NWJ) being employed for the reaming.



**Figure 6 - Goaf drainage boreholes**

This practice has many options in terms of distance from the roadway, height above the seam, trajectory, number and diameter of boreholes. The preferred option is to target a known coal seam for easier drilling (Figure 7) while alternative options are to drill along a design path at a prescribed vertical separation, either parallel to the working seam or at a prescribed vertical angle slightly up or down.



**Figure 7 - Goaf drainage borehole profile**

Access allows these boreholes to be installed along the length of tailgate side of the longwall block but drill site configuration is limited with boreholes having to be curved to suit (Figure 8).

### Water drainage and in-rush protection

Accessing coal seams above and below the current mining horizon has also been employed to provide water drainage of overlying or underlying flooded old workings (Hungerford, 2012). Being capable of drilling within these seams also allows drilling to provide in-rush protection from flooded old workings.



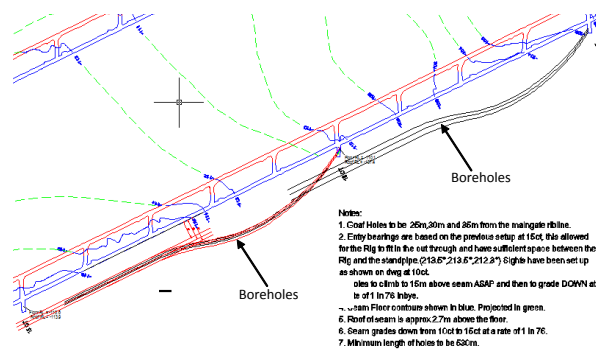


Figure 8 - Flanking goaf drainage boreholes

## Exploration

In-seam exploration drilling is usually confined to directional drilling within the working seam with progressive definition of the seam profile as the borehole advances. Intersection with a full displacement fault (Figure 9) requires cross-measure drilling to find the seam and define the displacement (Hungerford, 2011) to design further cross-measure drilling needed to continue drilling in the seam beyond the fault.

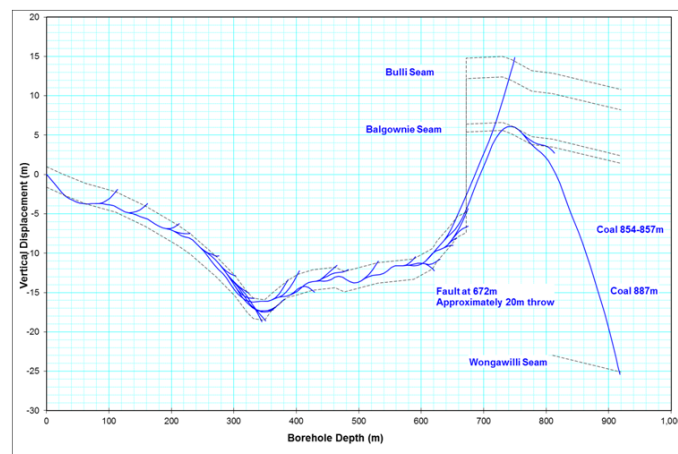


Figure 9 - Cross-measure in-seam drill for exploration (Hungerford, 2011)

## Cross-measure in-seam drilling for pre-drainage

A common practice in China is to drive roadways in stone below the working seam to provide access to rotary drill into the seam for pre-drainage (Figure 10) (Hungerford, 2008).

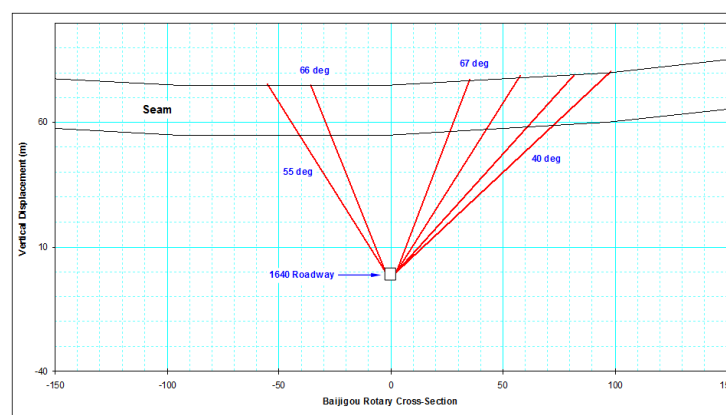
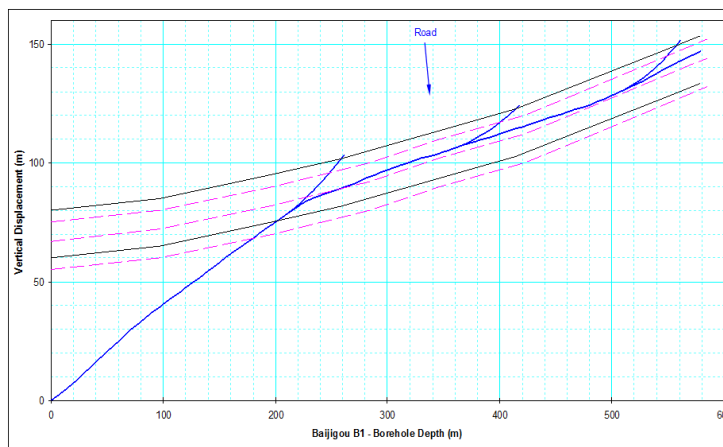


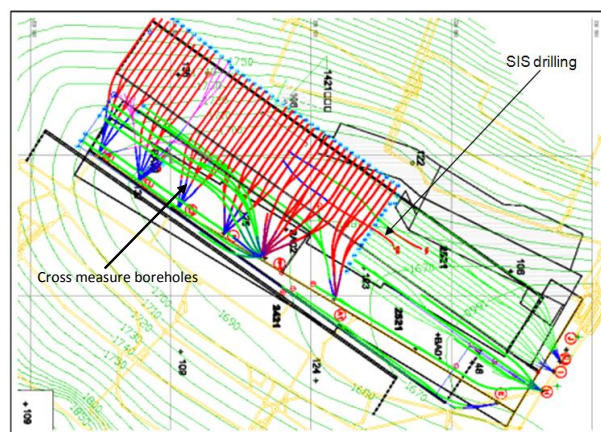
Figure 10 - Rotary cross-measure drilling for gas drainage (Hungerford, 2008)

A gas drainage project at Baijogou mine in China utilised cross-measure drilling to drain gas from a longwall block previously inaccessible from a below seam stone roadway (Hungerford, 2008). The drilling utilised tungsten tipped tri-cone bits to penetrate the 130 MPa stone up to the seam before reverting to PCD bits to drill the coal seam (Figure 11). The 20 m thickness of the seam allowed a more abrupt angle of intersection with the seam which assisted in managing instable conditions at the stone/coal interface. In most cases, two coal legs were drilled from each stone cross-measure section of drilling (Figure 12).



**Figure 11 - Baijogou cross-measure in-seam profile (Hungerford, 2008)**

The project involved two stages. The original cross-block drilling was followed by along block drilling to replace a failed attempt of SIS drilling (Figure 12). The stone drilling sections of each borehole are shown in blue.



**Figure 12 - Baijogou gas drainage layout (Hungerford, 2008)**

## CONCLUSIONS

The development of directional drilling for in-seam drilling has provided the coal mining industry the technology to accurately position boreholes within the working seam for gas drainage, exploration, water management and in-rush protection. The ability to position boreholes through planned locations and horizons has opened the opportunity to use directional drilling for more applications.

Directional drilling is now regularly used in projects involving cross-measure drilling for:

- Pre-drainage of gas from seams other than the current working seam,
- Positioning boreholes in strata above the seam to enable post-drainage of gas from goaf zones above longwall blocks,
- Positioning boreholes in strata or seams under seams to allow post-drainage from zones of stress relief under longwall goaf,

- 
- Exploration ahead of development,
  - Water drainage, management and in-rush protection from flooded workings in seams other than the current working seam.

There are challenges in managing complicated drilling environments other than that found in coal seams when drilling outside the seam boundaries but as new conditions are encountered, drilling procedures and practices have evolved to manage them. As more experience is gained, the cross-measure drilling practices are becoming more manageable and creating opportunities for other applications.

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